A Multilevel Code-Shifted Differential-Chaos-Shift-Keying System

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Abstract

The M-ary differential-chaos-shift-keying (M-ary DCSK) system offers a good noise performance over an additive white Gaussian noise (AWGN) channel in the category of non-coherent detection chaotic systems. However, the way that the M-ary DCSK system utilizes the available Walsh codes results in a relatively low bandwidth efficiency. Moreover, the number of delay elements required at the transmitter and receiver increases exponentially with the number of bits per symbol. To overcome the aforementioned problems, we propose a Multilevel Code-Shifted Differential Chaos Shift Keying (MCS-DCSK) system in this paper. In the proposed MCS-DCSK system, the reference chaotic signal and the information-bearing chaotic signals are orthogonal and are transmitted in the same time slot. We show that the MCS-DCSK system significantly outperforms the M-ary DCSK system in terms of bandwidth efficiency and complexity. We also derive analytical BER expressions for the MCS-DCSK system over AWGN and multipath fading channels, and verify them with simulation results.

Index Terms

M-ary Differential-Chaos-Shift-Keying, Multilevel Code-Shifted Differential-Chaos-Shift-Keying (MCS-DCSK), BER Expression, Bandwidth Efficiency.

I. Introduction

Chaotic signals can be easily generated by low-cost and low-power devices. The non-periodic property of chaotic signals help enhancing the security of chaos-based communication systems [1]–[3]. Besides, chaotic signals inherently possess good correlation, wideband, and noise-like characteristics which make chaos-based systems also spread-spectrum systems. Therefore, chaos-based communication systems have the capability to mitigate degradation due to multipaths [4], [5]. The Differential Chaos-Shift-Keying (DCSK) scheme together with a non-coherent detector offers very good error performance over multipath channels [6], [7]. Hence, variants of DCSK system and their bit-error-rate (BER) performances have been widely studied [8]–[10].

DCSK systems belong to Transmitted-Reference (TR) category in which the reference and information-bearing chaotic signals are transmitted in two consecutive time slots. Thus the attainable data rate is halved. Several methods based on DCSK have been proposed to increase the data rate. In [11]–[15], the data rate is increased by giving up some of the BER performance or requiring a highly complex receiver in comparison to DCSK.

Different from the above methods, the initial condition modulation (ICM), which is based on chaotic signal separation, is a multilevel modulation scheme [16]. However, its BER performance at the low signal-to-noise ratio (SNR) region is very poor. In [17], an orthogonal chaotic vector shift keying digital communication scheme based on QCSK has been proposed to improve the transmission data rates but a highly complex receiver is required. High data-rate Code-Shifted DCSK (HCS-DCSK) [18], Multi-Carrier DCSK (MC-DCSK) [19] and its improvement scheme Multi-user OFDM-based Chaos Shift Keying (MU OFDM-DCSK) [20] are capable of transmitting multi-bits in one time slot. Nevertheless, HCS-DCSK needs to reproduce chaotic sequences at the receiver, which is hard to implement in practice; while MC-DCSK sacrifices spectrum resources for data rate and MU OFDM-DCSK employs pilots which highly increase the power consumption. In [21]–[23], the data rate is increased without expanding the bandwidth. In [24], an improved differential chaos-shift keying (I-DCSK) system has been proposed and it replaces the delay circuit used in conventional DCSK systems by time-reversal operations.

M-ary DCSK [25], which employs the orthogonality of Walsh code sequences to transmit multi-bits, is a generalization of the binary DCSK. It provides an optimal solution over an additive white Gaussian noise (AWGN) channel in the category of non-coherent detection of chaotic system by employing the Generalized Maximum Likelihood (GML) decision rule [26]. However, the way that the M-ary DCSK system utilizes the available Walsh codes results in a relatively low bandwidth efficiency. Moreover, the number of delay elements increases exponentially with the number of bits per symbol. In [27], a Generalized Code-Shifted DCSK (GCS-DCSK) scheme, in which the reference signal and the information-bearing signal are separated by Walsh codes and transmitted in one time slot, has been proposed. The GCS-DCSK receiver does not require any delay lines. However, in order to guarantee orthogonality between the signal sub-streams, the GCS-DCSK scheme utilizes only half of the code sequences of a Walsh code matrix for transmission. In addition, the noise performance degrades seriously compared with the M-ary DCSK system.

We propose a Multilevel Code-Shifted DCSK (MCS-DCSK) scheme in this paper to increase the Walsh code utilization and the bandwidth efficiency. In our proposed MCS-DCSK scheme, the overall transmitted signal is the sum of the reference signal and a number of information-bearing signals which are separated by Walsh codes. At the receiver, a number of delay elements are used to facilitate the separation and decoding of the signals.

Our contributions in this paper are summarized as follows:

1) A multilevel modulation scheme, called MCS-DCSK scheme, has been proposed. It can achieve a high data rate compared with the M-ary DCSK scheme.

2) The bandwidth efficiency and complexity of MCS-DCSK and M-ary DCSK schemes have been compared. The MCS-DCSK system outperforms the M-ary DCSK system in terms of bandwidth efficiency and complexity.

3) A closed-form approximate BER expression for the MCS-DCSK scheme over an AWGN channel and an analytical expression over a multipath channel are derived. The theoretical results are close to the simulation results and can therefore provide good BER predictions for the MCS-DCSK system.

This paper is organized as follows. Section II present the system models of MCS-DCSK. Section III derives the analytical error performance of the MCS-DCSK system and Section IV shows the simulation results. Finally, Section V draws some conclusions.

II. System model of MCS-DCSK

In this section, we firstly review the transceiver of an M-ary DCSK system using its equivalent discrete-time model, then the transceiver of MCS-DCSK is proposed, the bandwidth efficiency and complexity of the proposed system are analyzed.

A. The M-ary DCSK system

We denote $\mathbf{W}^{(M)} = \mathbf{W}^{(2^l)}$ as the Walsh matrix of order $M(M = 2^l,\ l = 0, 1, 2,\ \ldots)$, the m-th row $(m = 1, 2,\ \ldots, M)$ of $\mathbf{W}^{(M)}$ is given by

$$\mathbf{W}_m = [w_{m,1}, w_{m,2}, \ldots, w_{m,M}]. \tag{1}$$

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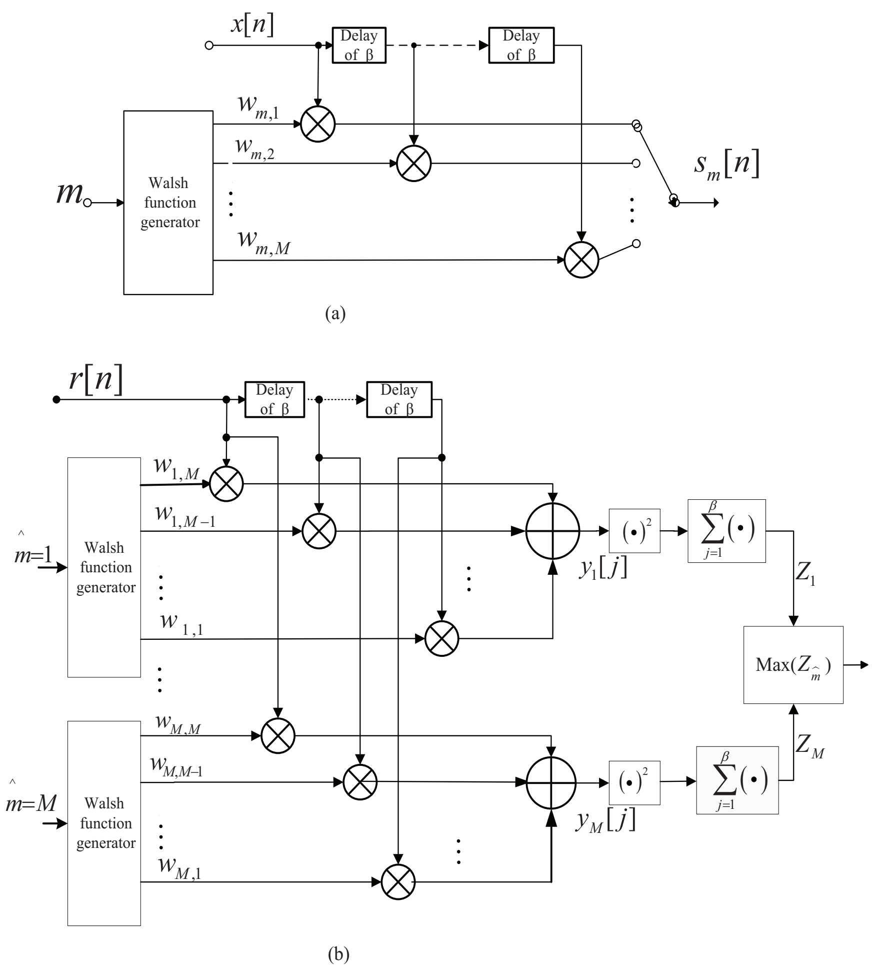

Fig. 1. The transmitter (a) and receiver (b) of an M-ary DCSK system.

The Walsh codes are used to orthogonalize the M-ary signals in the DCSK modulator. The mapping from binary bits $c_i (i = 1, 2, \ldots, l)$ to symbol m is governed by

$$\begin{cases} m = \sum_{i=1}^{l} c_i 2^{i-1} = \sum_{i \in D} 2^{i-1};\ l = \log_2(M) \\ D = \{k \mid c_k = 1,\ 1 \leq k \leq l,\ k \in \mathbb{Z}\}. \end{cases} \tag{2}$$

We define $\mathbf{x} = (x_1, x_2, \ldots, x_\beta)$ as a chaotic segment with length β. For every M-ary symbol, $M\beta$ chaotic signals will be sent. Supposing the symbol m is being sent, the n-th transmitted signal is given by

$$s_m[n] = s_m[(k-1)\beta + j] = w_{m,k} x_j \tag{3}$$

where $n = 1, 2, \ldots, M\beta \equiv (k-1)\beta + j$ with $k = 1, 2, \ldots, M$ and $j = 1, 2, \ldots, \beta$.

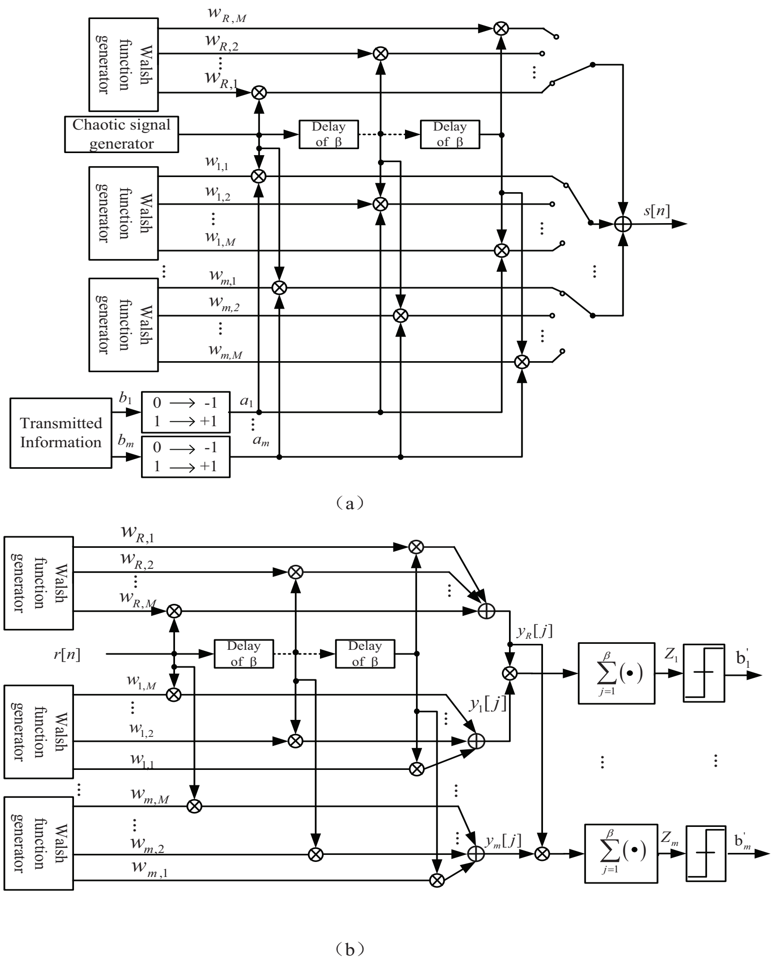

Fig. 2. The transceiver of MCS-DCSK scheme. (a) Transmitter (b) Receiver

At the receiver side, the n-th received signal, denoted by $r[n]$, is given by

$$r[n] = s_m[n] + \eta[n] = s_m[(k-1)\beta + j] + \eta[(k-1)\beta + j] \tag{4}$$

where $\eta[n] = \eta[(k-1)\beta + j]$ denotes the n-th sampled Gaussian noise with zero mean and variance σ^2. For the $\hat{m}$-th adder, the j-th output ($j = 1, 2, \ldots, \beta$), denoted by $y_{\hat{m}}[j]$, is given by

$$\begin{aligned} y_{\hat{m}}[j] &= \sum_{k=1}^{M} r[n] w_{\hat{m},k} \\ &= \sum_{k=1}^{M} \left(s_m[(k-1)\beta + j] + \eta[(k-1)\beta + j] \right) w_{\hat{m},k} \\ &= \sum_{k=1}^{M} \left(w_{\hat{m},k} w_{m,k} x_j + w_{\hat{m},k} \eta[(k-1)\beta + j] \right) \end{aligned}$$

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$$= \begin{cases} Mx_j + \sum_{k=1}^{M} w_{m,k}\eta[(k-1)\beta + j] & \text{if } m = \hat{m} \\ \sum_{k=1}^{M} w_{\hat{m},k}\eta[(k-1)\beta + j] & \text{if } m \neq \hat{m} \end{cases} \tag{5}$$

The output of the $\hat{m}$-th summation block, denoted by $Z_{\hat{m}}$, is therefore given by

$$\begin{aligned} Z_{\hat{m}} &= \sum_{j=1}^{\beta}(y_{\hat{m}}[j])^2 \\ &= \begin{cases} \sum\limits_{j=1}^{\beta}\left(Mx_j + \sum\limits_{k=1}^{M} w_{m,k}\eta[(k-1)\beta + j]\right)^2 & \text{if } m = \hat{m} \\ \sum\limits_{j=1}^{\beta}\left(\sum\limits_{k=1}^{M} w_{\hat{m},k}\eta[(k-1)\beta + j]\right)^2 & \text{if } m \neq \hat{m} \end{cases} \\ &= \begin{cases} \sum\limits_{j=1}^{\beta}\left(Mx_j + \sum\limits_{k=1}^{M} w_{m,k}\eta_{k,j}\right)^2 & \text{if } m = \hat{m} \\ \sum\limits_{j=1}^{\beta}\left(\sum\limits_{k=1}^{M} w_{\hat{m},k}\eta_{k,j}\right)^2 & \text{if } m \neq \hat{m} \end{cases} \end{aligned} \tag{6}$$

where $\eta_{k,j} \equiv \eta[(k-1)\beta + j]$. Finally, the symbol corresponding to the largest $Z_{\hat{m}}$ is demodulated.

B. The Transmitter of MCS-DCSK system

The block diagrams of transmitter and receiver of MCS-DCSK are shown in Fig. 2(a) and Fig. 2(b), respectively. The orthogonal Walsh codes are employed to bear reference signal and information bits. At the receiver side, the received signal of MCS-DCSK system is multiplied by the corresponding element of the reference Walsh code sequence and information Walsh code sequences and the products corresponding to reference Walsh code sequence and each information Walsh code sequence are added respectively.

As the inherent characteristics of Walsh codes, all rows of Walsh code are orthogonal to each other. In MCS-DCSK scheme, one row Walsh code sequence is chosen to transmit reference signal, the other rows are used to transmit information bearing signals.Without loss of generality, we assume that the M-th row of Walsh code sequence is used for the reference signal, i.e., $\mathbf{W}_R = \mathbf{W}_M = [w_{M,1}, w_{M,2}, \ \ldots \ , w_{M,M}]$. Note that if we assume that all the remaining $M-1$ Walsh code sequences have been used simultaneously to transmit $M-1$ information bit streams and all the $M-1$ information bits are 1's at the same time, the overall transmitted signal $s[n]$ (with the reference signal included) will become zero for the whole symbol period. Although this probability is small, it is non-negligible. To avoid such a scenario from happening, we should (i) refrain from using all the $M-1$ Walsh code and (ii) transmit an even number of bit streams at any time. By using an even number of bit streams, we can guarantee that the transmit signal will not become zero when the reference signal is included. Therefore, the maximum number of transmitted bits will be $M-2$. Apart from the M-th row of Walsh code sequence, any one of the remaining $M-1$ sequences can be used for transmitting the i-th bit. We define the Walsh code sequence for the i-th bit ($i=1,2,\ \dots\ ,M-2$) as $\mathbf{W}_i=[w_{i,1},w_{i,2},\ \dots\ ,w_{i,M}]$. As mentioned before, the first transmitted symbol is considered and the transmitted signal of MCS-DCSK, denoted by $s[n]$, is given by

$$\begin{aligned} s[n] &= s_n[(k-1)\beta+j] \\ &= s_R[(k-1)\beta+j]+\sum_{i=1}^{M-2} a_i s_i[(k-1)\beta+j] \\ &= w_{M,k}x_j+\sum_{i=1}^{M-2} a_i w_{i,k}x_j \end{aligned} \tag{7}$$

where $s_R[\cdot]$ denotes reference signal; $s_i[\cdot]$ is the un-modulated i-th bit signal; and $a_i \in \{+1,-1\}$ is mapped from $b_i \in \{1,0\}$ and is used to modulate $s_i[\cdot]$.

C. The Receiver of MCS-DCSK system

Assuming that the transmitted signal is corrupted by AWGN, the received signal $r[n]$ can be expressed as

$$\begin{aligned} r[n] &= s[n]+\eta[n] \\ &= s_R[(k-1)\beta+j]+\sum_{i=1}^{M-2} a_i s_i[(k-1)\beta+j] \\ &\quad +\ \eta[(k-1)\beta+j] \\ &= s_R[(k-1)\beta+j]+\sum_{i=1}^{M-2} a_i s_i[(k-1)\beta+j]+\eta_{k,j} \end{aligned} \tag{8}$$

where $\eta[n]=\eta[(k-1)\beta+j\equiv\eta[(k-1)\beta+j]$ denotes the n-th sampled Gaussian noise with zero mean and variance σ^2.

D. Bandwidth Efficiency

In the MCS-DCSK scheme, $M\beta$ samples are used to transmit $M-2$ bits of data. The bandwidth efficiency (BE) is hence given by

$$BE=\frac{M-2}{M\beta}. \tag{9}$$

Using a similar argument, the bandwidth efficiency of the M-ary DCSK system equals [28]

$$BE'=\frac{\log_2 M}{M\beta}. \tag{10}$$

TABLE I

COMPLEXITY OF MCS-DCSK SYSTEM AND M-ARY DCSK SYSTEM. R= RATIO OF THE NUMBER FOR M-ARY DCSK SYSTEM TO THAT FOR MCS-DCSK SYSTEM

Bits per symbol	System	M	Delay elements		Addition operations		Multiplication operations		Bandwidth efficiency
			Number	R	Number	R	Number	R	
2	MCS	4	3	1	19β-2	≈0.84	26β+8	≈0.92	$\frac{1}{2\beta}$
	M-ary	4	3		16β-4		24β		$\frac{1}{2\beta}$
6	MCS	8	7	9	103β-6	≈41	118β+48	≈35.8	$\frac{3}{4\beta}$
	M-ary	64	63		4224β-64		4224β		$\frac{3}{32\beta}$
14	MCS	16	15	1092	463β-14	≈579774	494β+224	≈543497	$\frac{7}{8\beta}$
	M-ary	16384	16383		268435456β-16384		268468224β		$\frac{7}{8192\beta}$
MCS=MCS-DCSK, M_ary =M_ary DCSK system									

Equations (9) and (10) indicate that for a fixed β and an increasing M, the bandwidth efficiency of the MCS-DCSK system gradually increases from $0.5/\beta$ to approximately $1/\beta$ while that of the M-ary DCSK system decreases from $0.5/\beta$ to almost zero. Therefore, the bandwidth efficiency gap between the two systems gets larger as M increases.

E. Complexity

In this subsection, we evaluate the complexity of MCS-DCSK and M-ary DCSK systems when both systems assume the same number of bits per symbol and the same parameter β. We determine the complexity by considering the number of addition operations, multiplication operations and delay elements in the transmitter and receiver. In Table I, we list the results when each symbol represents one bit, three bits and seven bits of information. We can observe that except for the case when each symbol represents two bits, the MCS-DCSK system has a slightly higher complexity than the M-ary DCSK system. However, for the other two cases, i.e., each symbol represents six bits and fourteen bits, the MCS-DCSK system achieves a much lower complexity than the M-ary DCSK system. The advantage of the MCS-DCSK system becomes more obvious as the number of bits per symbol increases.

III. BIT ERROR RATE ANALYSIS

We analyze the error performance of the MCS-DCSK system under an additive white Gaussian noise (AWGN) channel and a multipath fading channel in this section.

A. BER over an AWGN Channel

Since all the $M-2$ bit streams are independent and have the same error probability, we only need to evaluate the error performance of one of them. Considering the adder corresponding to the reference signal, the j-th output ($j = 1, 2, \ldots, \beta$), denoted by $y_R[j]$, is obtained as

$$\begin{aligned} y_R[j] &= \sum_{k=1}^{M} w_{M,k} r[n] \\ &= \sum_{k=1}^{M} w_{M,k}^2 x_j + \sum_{k=1}^{M} w_{M,k} \sum_{i=1}^{M-2} a_i w_{i,k} x_j + \sum_{k=1}^{M} w_{M,k} \eta_{k,j} \\ &= M x_j + \sum_{i=1}^{M-2} a_i x_j \underbrace{\left(\sum_{k=1}^{M} w_{M,k} w_{i,k} \right)}_{=0} + \sum_{k=1}^{M} w_{M,k} \eta_{k,j} \\ &= M x_j + \sum_{k=1}^{M} w_{M,k} \eta_{k,j}. \end{aligned} \tag{11}$$

Similarly, the j-th adder output corresponding to the m-th bit ($m = 1, 2, \ldots, M-2$), denoted by $y_m[j]$, is given by

$$y_m[j] = M a_m x_j + \sum_{k=1}^{M} w_{m,k} \eta_{k,j}. \tag{12}$$

At the end of the frame duration, the observation variable Z_m can be calculated as

$$\begin{aligned} Z_m &= \sum_{j=1}^{\beta} \left[\left(M x_j + \sum_{k=1}^{M} w_{M,k} \eta_{k,j} \right) \left(M a_m x_j + \sum_{k=1}^{M} w_{m,k} \eta_{k,j} \right) \right] \\ &= \underbrace{M^2 a_m \left(\sum_{j=1}^{\beta} x_j^2 \right)}_{T} \\ &+ \underbrace{M \sum_{j=1}^{\beta} x_j \left(\sum_{k=1}^{M} (w_{m,k} + a_m w_{M,k}) \eta_{k,j} \right)}_{U} \\ &+ \underbrace{\sum_{j=1}^{\beta} \left(\sum_{k=1}^{M} w_{M,k} \eta_{k,j} \right) \left(\sum_{k=1}^{M} w_{m,k} \eta_{k,j} \right)}_{V}. \end{aligned} \tag{13}$$

The variable Z_m can be decomposed into three terms, i.e., T, U, and V, respectively. The expectations and variances of these terms when $a_m = \pm 1$ can be easily derived as

$$\begin{aligned} &E\{T|a_m = +1\} = -E\{Z_m|a_m = -1\} = M^2\beta E\{x_j^2\} \\ &E\{U|a_m = \pm 1\} = 0 \\ &E\{V|a_m = \pm 1\} = 0 \\ &\mathrm{var}\{T|a_m = \pm 1\} = M^4\beta \mathrm{var}\{x_j^2\} \\ &\mathrm{var}\{U|a_m = \pm 1\} = 2M^3\beta E\{x_j^2\}\sigma^2 \\ &\mathrm{var}\{V|a_m = \pm 1\} = M^2\beta\sigma^4. \end{aligned} \tag{14}$$

Based on the above equations, the expectation and variance of Z_m given $a_m = \pm 1$ can be found as

$$\begin{aligned} E\{Z_m|a_m = +1\} &= -E\{Z_m|a_m = -1\} = M^2\beta E\{x_j^2\} \\ \mathrm{var}\{Z_m|a_m = \pm 1\} &= M^4\beta \mathrm{var}\{x_j^2\} + 2M^3\beta E\{x_j^2\}\sigma^2 \\ &\quad + M^2\beta\sigma^4. \end{aligned} \tag{15}$$

Using the central limit theorem, we approximate the decision variable Z_m as a Gaussian variable when $a_m = +1$ or $a_m = -1$. Therefore, the bit error rate (BER) of the MCS-DCSK system can be approximated by

$$\begin{aligned} BER_{AWGN} &\approx \frac{1}{2}\Pr(Z_m < 0|b_m = 1) + \frac{1}{2}\Pr(Z_m > 0|b_m = 0) \\ &= \frac{1}{2}\Pr(Z_m < 0|a_m = +1) + \frac{1}{2}\Pr(Z_m > 0|a_m = -1) \\ &= \frac{1}{2}\mathrm{erfc}\left(\frac{E\{Z_m|a_m = +1\}}{\sqrt{2\mathrm{var}\{Z_m|a_m = +1\}}}\right) \\ &= \frac{1}{2}\mathrm{erfc}\left[\left(\frac{2M^4\beta\mathrm{var}\{x_j^2\}}{M^4\beta^2E\{x_j^2\}^2} + \frac{4M^3\beta E\{x_j^2\}\sigma^2}{M^4\beta^2E\{x_j^2\}^2} \right.\right. \\ &\qquad \left.\left. + \frac{2M^2\beta\sigma^4}{M^4\beta^2E\{x_j^2\}^2}\right)^{-\frac{1}{2}}\right] \\ &= \frac{1}{2}\mathrm{erfc}\left[\left(\frac{1}{\beta} + \frac{2N_0(M-1)}{(M-2)E_b} + \frac{(M-1)^2N_0^2\beta}{2E_b^2(M-2)^2}\right)^{-\frac{1}{2}}\right] \\ &\approx \frac{1}{2}\mathrm{erfc}\left[\left(\frac{2N_0(M-1)}{(M-2)E_b} + \frac{(M-1)^2N_0^2\beta}{2E_b^2(M-2)^2}\right)^{-\frac{1}{2}}\right] \end{aligned} \tag{16}$$

where $E_b = \frac{M(M-1)\beta E\{x_j^2\}}{(M-2)}$ is the average energy per bit, $N_0 = 2\sigma^2$ denotes the noise power spectral density, and the last approximation assumes $1/\beta$ is very small compared with $\frac{2N_0(M-1)}{(M-2)E_b} + \frac{(M-1)^2N_0^2\beta}{2E_b^2(M-2)^2}$.

B. BER over a Multipath Rayleigh Channel

We assume a multipath channel with L independent and identically distributed (i.i.d.) Rayleigh-fading paths and corresponding gains denoted by α_l ($l = 1, 2, \ldots, L$). We again denote E_b as the energy per bit and N_0 as the noise power spectral density. Then the instantaneous signal-to-noise ratio (SNR) of the l^{th} path, denoted by γ_l, can be written as

$$\gamma_l = {\alpha_l}^2 \frac{E_b}{N_0} \tag{17}$$

and the instantaneous SNR per bit at the receiver, denoted by γ_b, is given by

$$\gamma_b = \sum_{i=1}^{L} \gamma_l = \frac{E_b}{N_0} \sum_{i=1}^{L} \alpha_l^2. \tag{18}$$

Assuming that the average power of all paths are identical, i.e., $E[\alpha_l^2] = 1/L$, the probability density function of γ_b is expressed as

$$f(\gamma_b) = \frac{1}{\bar{\gamma}(L-1)!} \gamma_b^{L-1} e^{-\frac{\gamma_b}{\bar{\gamma}}} \tag{19}$$

where $\bar{\gamma}$ denotes the average received SNR per path and is given by

$$\bar{\gamma} = \frac{1}{L} \frac{E_b}{N_0}. \tag{20}$$

The conditional BER as a function of γ_b is given by [29]

$$BER(\gamma_b) = \frac{1}{2} erfc \left[\left(\frac{2(M-1)}{(M-2)\gamma_b} + \frac{\beta(M-1)^2}{2(M-2)^2 \gamma_b^2} \right)^{-\frac{1}{2}} \right] \tag{21}$$

and finally the averaged BER of the MCS-DCSK system over a multipath channel equals

$$BER_{multipath} = \int_0^\infty BER(\gamma_b) f(\gamma_b) d\gamma_b. \tag{22}$$

IV. Simulation Results

We present some simulation results in this section. We assume that the chaos sequences are generated by the logistic map, which possesses mean and variance as $E\{x_j^2\} = \frac{1}{2}$ and $\mathrm{var}\{x_j^2\} = \frac{1}{8}$, respectively. We consider both an AWGN channel and a multipath channel. The statistical parameters of the multipath channel is as follows: $[E\{\alpha_1^2\}, E\{\alpha_2^2\}, E\{\alpha_3^2\}] = [\frac{1}{3}, \frac{1}{3}, \frac{1}{3}]$ with the delay vector $[\tau_0, \tau_1, \tau_2] = [0, 2, 4]$ indicating the delays in terms of the number of samples.

In Fig. 3, we plot the analytical BERs and the simulation results of the MCS-DCSK system versus E_b/N_0 over an AWGN channel when $M = 4$ and $\beta = 40, 100, 200$. We observe that the analytical results are close to the simulations, particularly when β is large. We also find that the BER results are better when β is small. In Fig. 4, we plot the BER results when $\beta = 100$ and $M = 4, 8, 16$. We can see that the

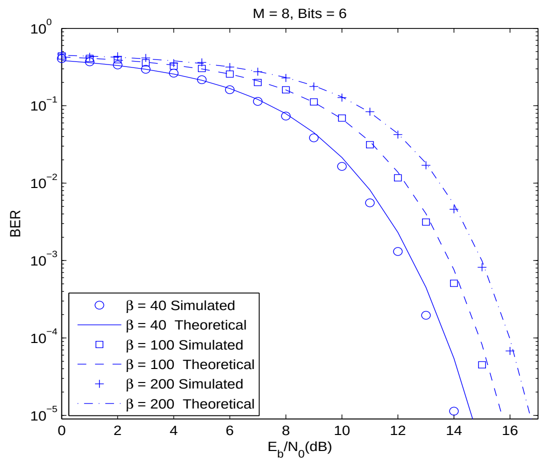

Fig. 3. Analytical BERs and simulated results of the MCS-DCSK system over an AWGN channel. $M = 8$ and $\beta = 40, 100, 200$.

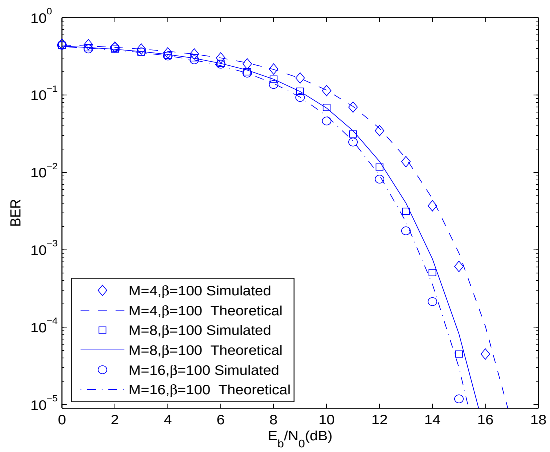

Fig. 4. Analytical BERs and simulated results of the MCS-DCSK system over an AWGN channel. $\beta = 100$ and $M = 4, 8, 16$.

analytical BER results are very close to the simulations. Moreover, the BER performance improves as M increases. It is because as M increases, a higher proportion of the transmitted energy $(M-2)/(M-1)$ is spent on sending the information bits.

In Fig. 5, we plot the BERs of the MCS-DCSK system and M-ary DCSK system over an AWGN channel and the three-path Rayleigh channel when both systems operate with the same bandwidth. Both systems use $M = 128$ and $\beta = 40$. However, the MCS-DCSK sends 126 bits per symbol while the M-ary DCSK system sends only 7 bits. Fig. 5 shows that the analytical BERs are very close to the simulations. There is a performance loss of the MCS-DCSK system compared with the M-ary DCSK

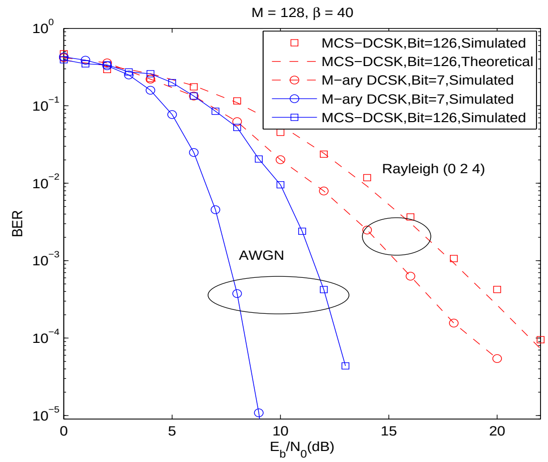

Fig. 5. Analytical and simulated BERs of the MCS-DCSK system and M-ary DCSK system over an AWGN channel and the three-path Rayleigh channel. Both the MCS-DCSK system and the M-ary DCSK system have the same bandwidth.

system under both AWGN and multipath Rayleigh channels. It can be explained by the different structures of the two systems. In the M-ary DCSK system, the binary bits are first mapped into a symbol which is then represented by one of the M orthogonal chaotic signals (with the use of an M order Walsh sequence). In the receiver, in order to demodulate the symbol, the GML decision rule is employed to find out the highest output among all the M summation blocks. Note that there are no interfering signals from other sources except noise. However, in order to improve the bandwidth efficiency and to have a lower transceiver, the MCS-DCSK system applies a different bit-to-symbol mapping rule (see (2)). As a result, there are interfering signals as well as an increase in noise level (U and V respectively in (13)). In summary, though the MCS-DCSK system requires 3 dB more compared with the M-ary DCSK system in order to achieve a BER of 10^{-5} over the multipath Rayleigh channel, the former system can accomplish an 18 times bit-rate improvement (or bandwidth efficiency improvement) over the latter one.

We also investigate the simulated BERs of the two systems over the same channel profiles when both systems operate with the same bandwidth efficiency of $1/512$. $M = 256$ and $\beta = 32$ are set for the MCS-DCSK system but only 16 out of the 255 Walsh codes are used for transmitting data. Moreover, $M = 4$ and $\beta = 256$ for the M-ary DCSK system. We can observe in Fig. 6 that our proposed MCS-DCSK system outperforms the M-ary DCSK scheme by about 4 dB at a BER of 10^{-3} under an AWGN or multipath channel. We find that the MCS-DCSK system can achieve a satisfactory BER performance when the parameters M, bits per symbol and β are selected properly.

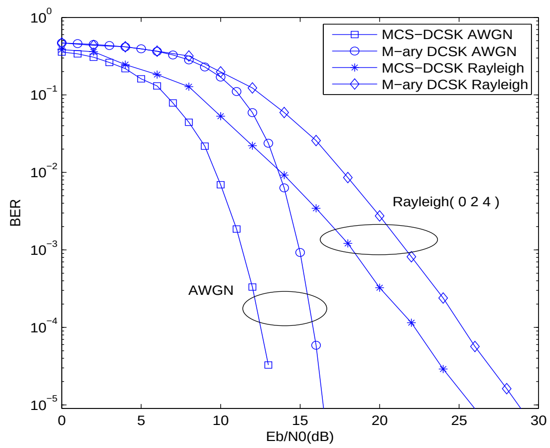

Fig. 6. The simulated BERs of the MCS-DCSK system and M-ary DCSK system over an AWGN channel and the three-path Rayleigh channel. Both the MCS-DCSK system and the M-ary DCSK system have a bandwidth efficiency of $1/512$.

V. Conclusion

In this paper, we have proposed a novel Multilevel Code-Shifted Differential-Chaos-Shift-Keying (MCS-DCSK) system. The proposed system utilizes one of the Walsh functions for the transmission of the reference chaotic signal and uses the remaining Walsh functions for the transmission of the information-bearing chaotic signals. To avoid sending an overall signal level of zero, the MCS-DCSK system can transmit at most $(M-2)$ bits per symbol when there are M Walsh functions. (Note that the traditional M-ary DCSK system sends only $\log_2 M$ bits per symbol when M Walsh functions are available.) We have also derived a closed-form expression to approximate the BER of the MCS-DCSK system over an AWGN channel and an analytical BER solution of the system over multipath fading channels. It is shown that the analytical BERs are close to the simulated ones, especially when the value of β is large.

The MCS-DCSK system has a lower complexity and high bandwidth efficiency compared with the M-ary DCSK system. The BER performance of the MCS-DCSK system is superior than that of the M-ary DCSK system under the same bandwidth efficiency, and vice versa under the same bandwidth. In view of its higher bit rate, the MCS-DCSK system can serve as another communication scheme for home entertainment networks.

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